

Pun and Cheung 2021 Meaning Making in Collaborative Practical Work: A Case Study of Multimodal Challenges in a Year 10 Chemistry Classroom

Abstract

Background

Constructing knowledge through collaborative practical work is a complex process and involves the use of multiple modalities by group members. In practical work sessions, students often manipulate visual objects or textual materials but do not develop their scientific ideas.

Purpose

This study illustrates (a) the challenges that science students face when they create thematic patterns in a laboratory class and (b) characterizes the processes of how students make meaning of practical work activities.

Sample

Drawing from a video database, we chose to investigate an 80-minute chemistry lesson with eight Year 10 students who were unpacking the complex ideas behind practical work. This lesson episode was transcribed multimodally, with snapshots of the pictures of students' actions and gestures.

Methods

This study adopts a case-study approach. A multimodal discourse analysis approach was taken to examine the classroom discourse of the students when they were determining the strength of acids and alkalis through electroconductivity.

Results

We identified various challenges when students integrated gestures, pictures and verbal discourse during practical work section. These challenges include those when students realize textual and visual modes and those when students associate components of apparatus into a system of functional set-up. Moreover, students cannot construct thematic patterns because they reorient their focus from the domain of ideas to the domain of objects and observables. The study recorded a number of strategies that students use to overcome these challenges that impede their meaning-making.

Conclusion

The findings of this study contribute to the literature by identifying the challenges and strategies faced by students when they were connecting the scientific ideas with the practical work. When science education researchers advocate inquiry-oriented approach, they should provide ample scaffolds for these multimodal challenges.

Key words

Chemistry; Meaning-making; Multimodality; Practical Work

Introduction

Previous educational research has focused on discourse in science classrooms. However, discourse in science classrooms does not only depend on linguistics resources, but it can be extended to various modes of resources such as actional and visual resources (Jewitt et al. 2001). Communication in science classroom requires integration of multiple meaning-making systems which are called “modes”. Discourse in science classrooms involves gestures, images, and written text, in addition to verbal communication (Brown and Spang 2008; Jaipal 2009; Kress et al. 2001). A representation is said to be multimodal if it comprises more than one mode and requires integration of the meanings behind these modes by learners. Multimodality focuses on the analysis on the synergetic effects across multiple representations (Tang 2013). For example, multimodal representations can be found in a textbook section as it shows a diagram of molecules and its written descriptions. Students and teachers often integrate the line (“bonds”) between atoms with the word “covalent bonds” and “sharing electrons” to make sense of how molecules are formed. If students only access the “lines” or the words “covalent bonds”, they cannot make meaning of how covalent bonds are formed. This notion is different from multiple re-representation, which only requires learners to create a representation that replaces the original representation (Tang, Tan, and Yeo 2010). Without integrating the meaning behind representations, representations will only confuse students (see examples from Cheng and Gilbert 2015).

Multimodality plays an important role in practical work in science classrooms, as it facilitates students’ learning in terms of scientific processes, skills and practical knowledge (Toplis and Allen 2012; Watson, Swain, and McRobbie 2007). Millar and Abrahams (2009) identified the two domains of ideas and of objects and observables in practical work. They suggested that practical activities are required to develop and connect these domains. However, they found that the quality and quantity of the science students’ discussions were relatively low when they conducted such activities (Watson et al. 2007). For example, the students seldom developed their ideas and linked them to the apparatus that they were manipulating (Abrahams, and Millar 2008). In a practical work, students need to collate, select and adapt information from different modes (Jewitt et al. 2001). Gesturing, verbal and actional resources are the semiotic resources which students often draw on when they are manipulating apparatus (Jewitt et al. 2001; McNeill et al. 2008). The experiment of dissecting pig kidneys requires students to understand the two-dimensional simplified diagram of kidneys and relate them to the real kidneys (Author 2, ongoing). Students need to correspond the terminologies such as “cortex” and “medulla” to the correct spatial position of the real pig kidneys. This requires integration across 2D diagrams, 3D real objects as well as the use of conventions (Cheng and Gilbert 2015). Not only do students need to understand single terminologies, they need to understand the semantic relationships among these terminologies. For example, the wall of blood capillaries is one-cell thick such that it shortens the distance of diffusion of glucose. It requires students to construct relationships among structures, behaviour and functions. Therefore, in a practical work setting, students may have to manipulate objects based on simple textual

representations and to make connections with other visual representations, as a necessary part of the curriculum.

Despite these challenges, some teachers might not see integration of different modes as the major concerns. In traditional practical work setting, teachers were worried about whether students can get the “correct” answers and what “ought to happen” in a practical work activity (Hodson 1993). Their attention is diverted to whether the experiment works instead of how students make sense of the practical work in the process of meaning-making. Practical work activities aim to help students identify questions and concepts behind investigations; develop and revise scientific explanations and models; address alternative models and explanations; make arguments based on the models they proposed (National Research Council 2006; Toplis and Allen 2012; Miller and Abrahams 2019) . Without understanding what challenges of integrating different modes students face, teachers cannot devise appropriate strategies to help students solve these challenges. It will be more difficult for students to carry out high-order reasoning as they can not make meaning from different multimodal resources.

Multimodal challenges may thus affect how science students develop ideas and their orientation of objects and observables in practical work activities. In this study, we extend the framework of Millar and Abrahams (2009) to characterise (1) the *multimodal challenges* that students face when attempting to integrate different modalities and (2) the challenges they face when developing their ideas, and the thematic patterns (Lemke 1990) they may use. We address the following two research questions. What challenges do science students face when they develop their ideas and when considering objects and observables? What strategies do they adopt to address these challenges? By taking a social semiotics perspective (Kress et al. 2001), we examine how knowledge construction is dependent on the integration of different modalities. We analyse data from a video-recorded practical science lesson taken from a large-scale project. In this lesson, students measured the electroconductivity of acids and alkalis to determine their strength. We conducted multimodal discourse analysis of a group of Year 10 students who participated in the lesson.

Backgrounds

Practical Work in Science Education

Practical work plays a central role in science education. It can illustrate to students the authenticity of science, and through activities they can experience scientific phenomena first hand. Skills and processes are considered to be as important as theories in science (Erduran and Dagher 2014) as they inform students about how science can be applied in practice. There are a wide range of practical work in science classrooms. It ranges from “cookbook” practical and inquiry-oriented practical work. Leonard (1991) stated that in some science practical work activities, students follow the procedures told by the teacher in a step-by-step manner. Erduran et al. (2020) coined this type of practical work as “cookbook” practical work since it does not involve any understanding behind the rationales of practical work. Practical work examples include electrolysis of molten salt, alkaline acid and separation of oxygen and nitrogen from air (Matthiessen and Pun 2017; Pun 2019).

Another end of practical work is practical scientific inquiry. In this type of practical work, students do not merely follow the procedures. They develop their own procedures to study real-life problems (Watson and Wood-Robinson 2002). Millar et al. (1994) observed how groups of children from 9 years old to 14 years old carried out practical scientific inquiry. It was reported that their ability to perform investigation tasks can be improved by teaching them the aims and the purposes of the investigations as well as the criteria of evaluating experimental data. Similarly, Watson et al. (2007) argue that practical work should be a scientific inquiry activity that allow students to discuss experimental design and the concepts behind. In the activity of studying the factors affecting the strength of paper chains, students did not justify their claims and their quantity of discussion was limited (Watson et al. 2007). Students simply used gestures to point the objects or used non-descriptive language such as “this one” (Watson et al. 2007).

Practical work in typical science classroom falls between “cookbook” practical and inquiry-oriented practical. Students commonly follow the procedures in the lab manual while they make sense of the results and concepts behind the scientific investigations. Millar and Abrahams (2009) argued that effective practical work should emphasise both what students ‘do’ with ideas and what they do with objects and materials. Millar and Abrahams conceptualised these foci into the two domains of ideas and of objects and observables. According to their framework, students can develop both domains and the connections between them through effective practical work. However, they observed 25 practical work lessons and found that none of the lesson aimed at helping students enquire processes. All lessons were to illustrate idea or practise experimental procedures. Moreover, in most lessons, teachers did not spend time on discussing the ideas and the models behind the practical work activity. Therefore, students rarely have the chance to discuss the ideas behind their practical work, and thus do not fully develop this domain of ideas (Krystyniak and Heikkinen 2007; Watson et al. 2007). If they are unable to connect their ideas to the observables and objects they are manipulating, the practical work will be less effective (see Figure 1).

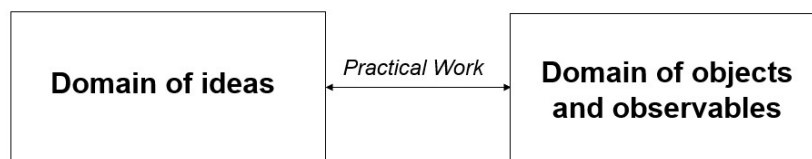


Fig. 1 The two domains in practical work (Millar and Abrahams 2009)

In the science classroom context, students typically work on practical tasks in groups. In a lab task, they are expected to discuss and conduct lab procedures and to record any noticeable results (Krystyniak and Heikkinen 2007). However, connecting what they learn from textbooks with this hands-on process requires students to match the cognitive knowledge they hold with procedural knowledge. This is comparable to the notion of connecting ideas with the domain of observables and objects (Millar and Abrahams 2009). Students often discuss *how* and *why* they use particular apparatus in a practical activity. The process through which students match their own ideas with observables in science investigations can be assessed by examining their interaction sequences in a lab class. Studies analysing verbal

interactions among students during practical activities have emphasised the issue of how students relate scientific theories and evidence in a practical work context (see examples from Krystyniak and Heikkinen (2007) and Watson et al. (2007)). However, these studies have focused on verbal interactions, instead of exploring how students use multimodal resources in their discourse. Science classroom discourse includes not only verbal communication, but often also gestures, images and verbal and written text (Brown and Spang 2008; Jaipal 2009). These multimodal semiotic resources enable students to make meaning of the science behind the activities.

Multimodality in the Domain of Objects and Observables

'Multimodal representations' refers to 'the integration in science discourse of different modes to represent scientific reasonings and findings' (Prain and Waldrup 2006, 1844). This differs from the term 'multiple representations', which refers to re-representing the same concepts through different forms, such as diagrams, texts and graphs (Prain and Waldrup 2006). Kress et al. (1998) suggested that four modes of communication are typical in science discourse: speech, images, gestures and material apparatus. Ainsworth (2006) argued that learners must integrate these different representations to benefit from them. A mode can be "focal" when it forms the centre of a meaning-making activity, and other modes of communication are often related to the focal communicative mode (Kress et al. 1998). For example, teachers can use language to reorient students' attention to the map. Talk becomes the focal communicative mode at the first instance and the image of the map becomes focal afterwards. When the teacher showed the movement of plates in the map, talk recedes and gestures foreground other modes. Williams (2020) also examined the modes used by Hong Kong students in content-based science lessons. He identified that students' use of gestural and tactile modes enabled them to participate in science discourse and to make meaning of science content in scientific inquiry. These modes can facilitate science discourse in four different ways: replacement, support, demonstration and imitation. The focal communicative mode is constantly shifting from one segment to another segment in the lesson episode.

The integration of modes becomes more difficult as the number of modes of representations increases (Tang et al. 2010). In the study by Tang et al. (2010), integration of mathematical representations, gestures and spatial representations are necessary for students to understand work-energy concepts. It requires students to connect reasoning, calculation, visual representation, real-world connection and declarative knowledge together to make sense of complex relationships. We coin these challenges as "multimodal challenges" which refers to learners' difficulties in connecting one mode to another in the process of meaning-making. In the context of practical work, the number of modes of representations is more than that in normal science lessons, because it often involves diagrams of set-up, tactile, apparatuses, gestures and speech. Only a few research studies could address the difficulties that student face when they draw on multimodal semiotic resources to develop their domain of ideas in practical work. The present study aims to answer this question by studying their multimodal challenges and hence how they impede the development of the domain of ideas.

Thematic Patterns in the Domain of Ideas

In science discourse, content is mainly understood and communicated through

language (Axelsson and Jakobson 2020). Abrahams and Millar (2008) argued that for practical work to be effective, students must not only know how to manipulate the objects, but also communicate the scientific ideas behind the practical work. Language serves as a meaning-making tool through which students can communicate and develop their ideas during practical activities. By analysing the language of the participating students from a social semiotics perspective (Kress et al. 2001), we could examine how they developed meaning.

We identified thematic *patterns* in the language used by the students in their practical activities. Lemke (1990) defined thematic patterns as those emerging from the various semantic relationships among words. Teachers can suggest thematic development strategies to students, which they can draw on when constructing new scientific knowledge. Lin and Lo (2017) identified monologue and dialogue strategies as the main thematic development strategies applied by science teachers in Hong Kong. Monologue strategies can involve teachers selectively summarising students' discourse, and dialogue strategies can entail teachers asking a series of questions or selecting and modifying students' responses. However, this focus on the role of teachers in developing thematic patterns can be enhanced by an examination of how students can jointly construct these patterns. Practical science work can be particularly conducive to their co-construction of such thematic patterns.

Research Context

The aim of this study is to expand the framework by Millar and Abrahams (2009) such that the modified framework can characterize multimodal challenges that impede thematic development and capture the strategies used by students to overcome these challenges. The research team consists of an academic in science education (first author), a teacher-researcher (second author) and a research assistant. The research team met to select lesson videos from the first author's PhD project (see Author 1 (under revision)) according to the following criteria: (1) it should involve group practical work activities; (2) students are engaged in development of thematic patterns; (3) the practical work should involve students' integration of different modes. His PhD project is an ethnographic study that examined students' and teachers' use of the medium of instruction (MOI) and multimodality in science classrooms. After several rounds of re-watching of videos, we identified an 80-minute lesson episode. This lesson episode was taken from a tenth-grade chemistry class in a Band 1 public school in Hong Kong. Secondary schools in Hong Kong are classified into three bandings: Band 1, Band 2 and Band 3. Band 1 schools admit students with the highest academic ability, while Band 3 admit students with comparatively lower ability. The admission is based on students' results in primary schools.

This school follows the typical Hong Kong curriculum which comprises a three-year junior science curriculum and a three-year senior science curriculum. In the senior science curriculum, students can choose whether they study science subjects or arts subjects. Chemistry, biology, physics are the three subjects offered by the school in their senior science curriculum. The medium of instruction is English, but we can see that the teacher used Cantonese when he was communicating with individual students. This project received ethics clearance through the University of Oxford Central University Research Ethics Committee in March 2014. All participants

were assured of confidentiality and anonymity to ensure that neither individuals nor their schools could be identified.

In the lesson episode, students determined the strength of acids and alkalis by measuring their electroconductivity. Students had a basic understanding of acid and alkalis when they learnt science in Year 8. However, they did not have the concepts of ions when they learnt acid and alkalis in Year 8. Before the practical work activity, they learnt how to explain the strengths of acid and alkalis with reference to the dissociation of ions. Although they knew that the strength of acids and alkalis can be reflected by electroconductivity, they did not know the exact procedures of measuring it. They also had some basic understandings of power, current and voltage when they learnt the topic “Making Use of Electricity” in Year 8. The teacher who taught this lesson held a bachelor’s degree in chemistry and teacher certificate in chemistry education in Hong Kong. He has taught chemistry for five to six years. He first provided students with four different chemicals, diluted hydrochloric acid, diluted ethanoic acid, diluted ammonia solution and diluted sodium hydroxide. Moreover, he provided students multimeter (charged by lithium batteries), carbon electrodes, wires with clamps (crocodile clips).

Afterwards, he gave students a practical manual with procedures, but he did not demonstrate how to connect the power pack and wires together. He drew a circuit diagram to illustrate the connections, which the students referred to along with the lab manual when connecting the apparatus. During the practical activity, he circulated around and questioned students’ explanations of the current recorded for different acid and alkalis. The first author was present in the classroom when the lessons were recorded. All of the recorded data were transcribed and translated where necessary from Cantonese into English by the first author using NVivo software.

Figure 2 illustrates the complexity of this integration during the practical activity of measuring the electroconductivity of acids and alkalis. The students received various visual and textual inputs before they began, including a diagram in the practical manual, a general circuit diagram and procedural text. Through collaborative realisation (Kress et al. 2001), they linked each piece of apparatus to the objects. They collaboratively associated (Kress et al. 2001) each object to create an experimental set-up system. Building a circuit to measure electroconductivity required them to recognise the properties of wires, a multimeter, a power pack and a solution (acid or alkali), and then to assemble them. As this involved numerous modes, it created *multimodal challenges* for the students in assembling the apparatus into a functional system. Ainsworth (2006) suggested that one type of representation can constrain another type, and so if students encounter too many multimodal challenges in a practical activity, they will put less effort into developing their ideas.

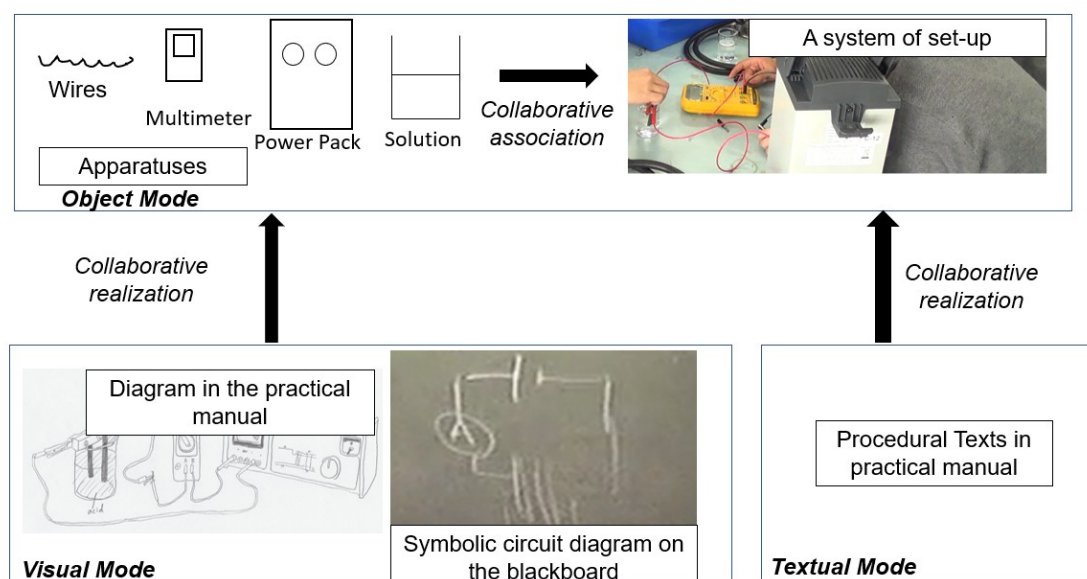


Fig. 2 The integration of different modes in measuring electroconductivity of acid and alkalis

Data Analysis

The lesson episode was transcribed multimodally. The research questions form an overarching framework to help us identify the lesson episodes that are related to (1) negotiation of multimodal challenges by students and (2) students' development of thematic patterns. To analyse multimodalities in the lesson, the first author and the second author identified the sequence of modalities students used in each turn of talk independently. The second author is an experienced science teacher-researcher at a local school. His research expertise is multimodality in science education and is familiar with Lemke's (1990) framework. After identifying the modes that students use, the second author analyses the communicative function of each turn. These procedures are similar those by Jaipal (2010). After several rounds of discussion, both authors came into consensus on the themes emerged under each of the research question.

Regarding students' development of thematic patterns, both authors read the transcripts independently and identified the patterns according to the framework extended from that of Millar and Abrahams (2009). The analyses were then compared, and any disagreements were resolved through discussion. Inter-rater reliability may not be appropriate when analysing discourse of a qualitative and descriptive nature (Author 2, under review), so we chose to use member checking to establish our reliability. We thus shared our interpretation of the data with another experienced teacher at a local school who had conducted research into multimodalities in science education.

Findings

Integrating Multimodalities in Practical Activities

Multimodal challenges in practical work Students encountered challenges in recognizing the role and functions of each apparatus and equipment. As shown in Table 1, the teacher did not explain how to connect the set-up for measuring the electroconductivity of acid and alkali. He expected the students to be able to do this themselves. We can see S1 who used speech to question the roles and functions of apparatuses for several times, as indicated by turns 5 and 10 in the excerpt shown in Table 1. He encountered difficulties in recognizing the role of black wire (turn 5) and the role of multimeter (turn 10). Though the apparatus provided is a multimeter, S1 perceived it as a voltmeter (turn 5) and S4 perceived it as an ammeter (turn 10). Therefore, it shows that S1 was confused about the identity of the yellow device. And other students were only familiar with voltmeters and ammeters instead of multimeters.

Table 1

Collaborative realisation of visual and textual modes

Turn	Speech	
1.	S?	Get the solution first.
2.	S1	80 cm ³ of 0.1 mol ethanoic acid (reading out the lab manual) in the small beaker. 80 cm ³ .
3.	S2	Connect the wire (holding the wire, reading out the procedure)
4.	S1	Where is the battery? (holding the multimeter)
5.	S1	Black is positive?
6.	S1	Black (wire) can be inserted to here.
7.	S3	Insert it first!
8.	S4	Now are we doing part (a) (of the lab manual) ? (asking S1)
9.	S1	Maybe. (looking at the lab manual) Put this one to this one.
10.	S1	This is a voltmeter? (touching the ammeter)
11.	S4	Ammeter.
12.	T	What? You haven't turned on the switch.

Students also had difficulties in realizing written procedural texts and the visual diagrams into the object mode. In turn 4 in Table 1, the lab manual had a picture that could help students identify the multimeter, but student S1 experienced difficulties operating it. He tried to find the battery, but its location was not given in the lab manual. He then attempted to connect the wires. Each group was given red wires and black wires, but as Figure 2 shows, the wires in the lab manual picture were not coloured, and the written instructions did not say which colour was positive. In turns 10-11, although the instructions and the diagram in the lab manual stated that the device used to measure current is a multimeter, the students could not translate this textual information into the object mode. The visual and textual modes posed *multimodal challenges* for the students as they cannot connect the visual mode of diagrams and the written text to the object mode.

Another challenge is that students had difficulties in associating individual apparatus into a system of *functional* apparatus. To obtain readings from the multimeter, the students had to connect the wires to the power box, link the carbon electrodes to the multimeter and connect the multimeter to the power box. The students experienced multimodal challenges in assembling a functional system from

407 the equipment as the connecting was somewhat complex (see the excerpt in Table
 408 2). The roles of the various components had to be constantly examined to ensure
 409 that the set-up was functional. As indicated in turns 3-6, speculation about these
 410 roles was confirmed by peers. In turn 3, S2 expressed his lack of confidence, saying,
 411 'No I don't know how to insert this wire'.
 412

Table 2

Collaborative association of apparatus into a functional system

Turn	Speech
1 S3	You need to clamp it first. That one is incorrect. . <i>(S2: Clamping the wire into the pH meter and others are fiddling with the wires to see where it should go)</i>
2 S4	You guys are so smart!
3 S2	No I don't know how to insert this wire
4 S3	This one. This one. This position. Yes. . <i>(pointing to the "right" wire that connects to the pH meter)</i>
5 S5	Put the 'Current' first.
6 S3	You just put it inside the wire. Put it inside. . <i>(points his head towards the red wire by telling him to add it inside the water)</i> <i>(Student 4: tries to put the wire inside the water to see if it works, uses the back as a guide to carry out the experiment)</i>
7 S3	Isn't it supposed to be like this?
8 S4	Then try turning on this one. Don't turn it on yet.
9 S3	You connect this one first. This clamp should go here. The wire goes down to the bottom one.
1 S1	No this one doesn't go here.
0	
1 T	I was thinking about how to connect to this switch.
1	
1 S2	No, it's okay if you put it that way. It's fine. 2 <i>(Student 4: puts the red wire inside the pH meter and adjusts it accordingly)</i>
1 S1	Cell. This cell 3 <i>(Student 1 instructs him to use the cell instead where student 1 connects the black and red wire together.)</i>
1 S1	This is not right. This should be placed in another way. Not here. What 4 will this be when lithium (battery) is added to it? . <i>(Student 1 gives an alternate solution and points to the black wire)</i>

413

414

415

Strategies to overcome multimodal challenges If both students encountered

challenges in integrating different modes of representations, they sometimes gave reassurance to their peers. As shown in turns 5-7 in the excerpt shown in Table 1, S1 was confused about whether he should connect the black wire or the red wire to the positive terminal of the power pack. Though S3 did not know how to solve S1's confusion, S3 still said to S1, '*Insert it first!*' Students often encourage their peers to try and follow experimental procedures in collaborative group work, even if they do not fully understand the role of each piece of equipment. Moreover, as shown in the excerpt in Table 2, S3 reassured S2 by repeatedly saying '*This one!*', using a gesture to indicate where the wire should be inserted. Turns 7-10 show the students speculating about how they should connect the wires, crocodile clips and electrode cells. S3 asked, '*Isn't it supposed to be like this?*' S4 also encouraged S3 to turn on the multimeter to see whether they could obtain a reading. Although the students experienced difficulties filling in the gaps in terms of the textual and visual modes in the practical manual, they encouraged their peers to overcome these multimodal challenges.

Another strategy the students used was to express evaluative judgements to avoid their peers from making mistakes. If one student knew how to solve the multimodal challenges, he will instruct his peers to find the correct way to realize the visual mode and the object mode. As shown in the excerpt in Table 2, '*No this one doesn't go here*' in turn 10 and '*This is not right. This should be placed in another way. Not here*' in turn 14 have guided their peers and have been in control of how the group carried out practical work activity.

Co-construction of Thematic Patterns to Develop the Domain of Ideas

The development of ideas during practical activities can be facilitated by both students and teachers (Millar & Abrahams 2009). Millar and Abrahams (2009) suggested that students should think about the concepts behind practical activities, and Lin and Lo (2017) argued that by examining how students develop thematic patterns, researchers can understand the co-construction of scientific concepts by students and teachers. Thematic patterns are the semantic relations between words (Lemke 1990). These patterns were found in this lesson episode, based on Lemke's (1990) seminal work (refer to Table 3).

Table 3. Thematic patterns, their descriptions and the quotes from the episode

Thematic Patterns	Descriptions	Quotes from the episode
<i>process/reason</i>	the reasons why the process takes place	S5: Sir, are you lying to me? Why does it show 0 (A) (in the multimeter)? S1: Insulator
<i>meronym/holonym</i>	a constituent part of a whole	T: Because they (acid) <i>have</i> mobile ions.
<i>attribute/carrier</i>	the descriptive characteristics of objects	T: They (acid) <i>are</i> conductors.
<i>item/variation</i>	A, but not B	T: But one (hydrochloric acid) can conduct better, another (ethanoic acid) does not.
<i>location/located</i>	the spatial relationships of	S6: 'Chlorine gas' is ' <i>in the</i>

	objects	<i>swimming pool</i>
<i>agent/process</i>	the entity acts	S5: It (chlorine)'s for cleaning the teeth.

Lin and Lo (2017) suggested that teachers can use various thematic development strategies to help students construct thematic patterns, including monologue and dialogue strategies. We identified instances in which teachers tried to help the students develop thematic patterns. Using a multimodal discourse analysis approach, we examined why the students did not construct complex thematic patterns during their practical work.

Reorienting the discussion from the domain of ideas to the domain of objects and observables After the students assembled the apparatus, they measured the electroconductivity of acids using a multimeter (see the excerpt in Table 4). Electroconductivity indicates the strength of an acid by showing the concentration of mobile ions in the solution. The students compared the strength of hydrochloric acid and ethanoic acid solutions using the multimeter. At one point the multimeter gave a zero reading. One student (S5) asked the teacher, '*Sir, are you lying to me? Why does it show 0 (A) (in the multimeter)?*' (process). Another student (S1) responded with the word '*insulator*' (reason). This shows that a 'process/reason' relation was co-constructed by the students when considering why the multimeter showed a reading of zero.

Once the teacher realised that the group had obtained a zero reading, he was surprised that S1 said that acid is an insulator. He tried to help students develop their domain of ideas through a monologue. He asked the rhetorical question '*Why do we need to measure this?*' and signalled that there should be something that can conduct electricity. He then answered '*Because they (acids) have mobile ions*', thus building a meronym/holonym relation between the meronym 'mobile ions' and the homonym '*they (acid)*'. He expressed the attribute/carrier relation that '*they (mobile ions)*' are '*conductors*'. He then explained the *item/variation* that hydrochloric acid '*can conduct better*' while ethanoic acid '*does not*'. Although the teacher explained why the reading of zero on the multimeter of zero should not be due to the presence of ions in the acid solution, one student (S5) diverted the group's attention by asking '*But why does it show zero?*' S5 thus reoriented the focus of why hydrochloric acid gave a higher reading than ethanoic acid to the functioning of the system of apparatus. The whole group then focused on finding the errors in connecting the wires and the carbon electrode. Thus, the teacher and the students could not capitalise on the opportunities to expand the thematic networks by explaining why the multimeter readings for hydrochloric acid and ethanoic acid were different.

Table 4
Reorienting the discussion from the domain of ideas to the domain of objects and observables

S 5	00:10:00	00:10:02	Sir, are you lying to me? Why does it show 0 (A) (in the multimeter)? (S5 is pointing at the multimeter with 0A shown in the reading)
S 1	00:10:16	00:10:17	Insulator
T	00:10:31	00:10:41	Oh you have studied the whole F4. We're talking about.

Why do we need to measure this? Because they (acid) have mobile ions. They are conductors. But one (hydrochloric acid) can conduct better, another (ethanoic acid) does not.

S 00:10:42 00:10:43 But why does it show zero?

5

T 00:10:46 00:10:47 It is wrongly connected.

489

490 According to Lin and Lo's (2017) suggestions, the teachers could have engaged
491 the students in constructing thematic patterns through thematic development
492 strategies, such as asking them to give the expected answers, selecting and
493 modifying their answers or selectively summarising their answers. The excerpt
494 shows that the teacher could have used such strategies to help the students
495 construct thematic patterns. Although the teacher expressed attribute/carrier,
496 item/variation and meronym/holonym relations in terms of the main thematic item of
497 'ammeter reading', the students only constructed a process/reason relation for the
498 thematic item of 'zero reading'. The teacher's monologue meant that the students
499 had fewer opportunities to construct complex thematic patterns. For example, the
500 teacher could have asked the students to explain the attributive meaning of 'mobile'
501 for ions. Without understanding the semantic relation between scientific terms such
502 as 'mobile ions' and 'conductors', the students shifted the focus of their discussion to
503 the domain of objects and observables from the domain of ideas. Our interpretation
504 of the classroom discourse was also supported by the chemistry teacher who had
505 previously examined the students' scientific discourse. He explained that 'mobile
506 ions' and 'conductors' are abstract scientific terms that require teachers to mobilise
507 multiple semiotic resources to help students link their meanings to the experimental
508 set-up.

509

510 **Students afforded opportunities for co-constructing thematic patterns**

511 Although the teacher did not always offer students opportunities to construct
512 thematic patterns, the students could afford the opportunity to co-construct
513 knowledge by elaborating the semantic meanings of the thematic items (see the
514 excerpt in Table 5). When a student tried to turn the voltage of the powerpack right
515 up, the teacher stopped him by saying '*Don't turn (the powerpack) to too high a
516 current. There will be chlorine gas*'. One student (S4) did not know what he was
517 talking about, because he was not aware that the experiment could produce chlorine
518 gas. The teacher tried to explain using the Cantonese translation of chlorine gas, '氯
519 氣'. After he turned away, S4 still did not understand why they could not turn the
520 powerpack power to high.

521

522

Table 5

Students afforded opportunities for co-constructing thematic patterns

Speaker	Time	Speech
T	00:14:23 00:14:25	Don't turn (the powerpack) to a too high power. There will be chlorine gas. (S3 is turning the powerpack.)
S4	00:14:25 00:14:26	What does that mean?
T	00:14:27 00:14:28	氯氣 (Cantonese translation of chlorine gas) (the teacher turned away)

S6	00:14:31	00:14:32	In the swimming pool.
S5	00:14:32	00:14:37	It's for cleaning the teeth.

S5 and S6 knew that S4 did not understand the teacher's explanation, so they *afforded opportunities* by elaborating the thematic relations of 'chlorine gas'. One student (S6) expressed the 'location/located' relation, saying that 'chlorine gas' is '*in the swimming pool*'. Another student (S5) responded by expressing the transitivity process relation, saying that 'chlorine gas' could be involved in '*cleaning the teeth*'. In this 'agent/process' relation, 'chlorine gas' represents an actor, 'clean' represents a process and 'the teeth' represents an agent. However, these thematic patterns could have been further developed, because (1) they did not connect 'chlorine gas' to the domain of objects and observables, such as why the gas was produced in the experiment; and (2) the thematic relation involved a misunderstanding of the thematic item, as fluorine rather than chlorine is used to clean teeth. This excerpt shows that although the students tried to establish the basic relations of the thematic item 'chlorine', they could have related 'chlorine gas' to the reasons why they could not turn the powerpack up. The teacher should have explained that chlorine gas is produced through the electrolysis of hydrochloric acid. He should also have explained that the gas is toxic, and thus should not be produced in large quantities during the experiment.

Discussion and Implications

In this study, we extended the framework of Millar and Abrahams (2009) to characterise the process of knowledge construction for a group of Year 10 students engaged in practical work (see Figure 3). To examine their idea development, we observed how they developed thematic patterns (Lemke 1990). To examine their development in the domain of objects and observables, we observed how they integrated modalities such as gestures, speech, images and objects (Kress et al. 2001). We conducted a detailed analysis of the discourse of a group of Year 10 students when they were measuring the electroconductivity of acids and alkalis. Although the students experienced different challenges that impeded their development in both domains, they were able to use coping strategies to overcome these challenges in their practical activities (shown in Figure 4).

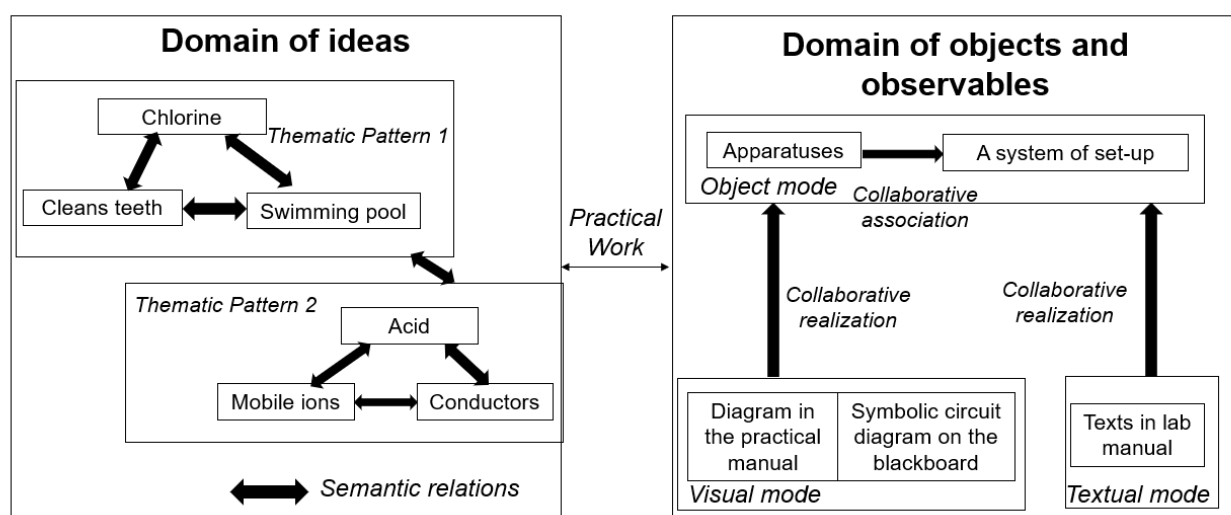


Fig. 3 A modified and expanded framework for characterizing the development of domain of ideas and domain of objects and observables in practical work

Our findings add to this research by highlighting two major areas of difficulties that are specific to multimodalities in practical work: (1) the collaborative realisation of visual and textual modes into the object mode; and (2) the collaborative association of individual apparatuses into a *functional* system through gestures and movement. Students cannot translate from textual mode and visual mode to the object mode. It might be because the written procedures in the practical and the diagram of the set-up are abstract in nature and it requires students' integration to realize them into object mode. Moreover, they cannot associate individual apparatus into a system of functional apparatuses. Without explicit instruction on how to make meaning of these modalities, it is very difficult for students to develop their understanding of different modes of representations. For example, the diagram of the set-up shows wires as a series of "lines", but students face red wires and black wires in the experiments. However, the procedures in the lab manual asked them to "connect the wires". They did not have further guidance on how to connect the wires. If teachers do not have explicit instruction on how to use and connect these wires, it is difficult to expect students to connect these "lines" in the diagrams to the real wires of different colours. Without knowing how to work with individual apparatus, it is difficult for students to connect these apparatuses to carry out a *functional* experiment. In the excerpts we provided, students spent a lot of time to assemble the wires and to connect the wires to the power pack as well as the multimeter, as the multimeter kept showing zero reading. Tang et al. (2010) similarly found that students encountered difficulties when attempting to integrate spatial and mathematical representations. However, most studies have focused on how teachers help students connect multimodal resources to construct knowledge in standard science lessons (Brown & Spang, 2008; Jaipal, 2009). To make progress in practical work, students can use strategies such as encouragement and expressing evaluative judgements of their peers, thus integrating different modes of representation (see Figure 4).

	Domain of ideas	Domain of Objects and Observables
Challenges	<u>Thematic Patterns Challenges</u> <ul style="list-style-type: none"> • Reorienting the Discussion from the Domain of Ideas to the Domain of Objects and Observables • Teacher's monologue strategies 	<u>Multimodal Challenges</u> <ul style="list-style-type: none"> • Translating from textual mode and visual mode to object mode • Associate separate objects into a system of functional apparatus
Strategies to overcome these challenges	<ul style="list-style-type: none"> • Students afforded opportunities to co-construct thematic patterns 	<ul style="list-style-type: none"> • Evaluative judgements by peers • Encouragement and reassuring by peers

Fig.4 Challenges and strategies in developing domains in practical work

Although the development of ideas is one ultimate aim of practical work (Millar and Abrahams 2009), few studies have explored why some students can or cannot

develop their ideas. We highlighted episodes in which students diverted their attention from the development of ideas to the domain of objects and observables, possibly because they paid too much attention to integrating different mode of representations. As shown in the excerpt in Table 4, when a student asked why the multimeter showed no current, the teacher tried to help students to develop the semantic relations among “acids”, “conductors” and “mobile ions” (refer to thematic pattern 1 in Figure 3). Due to the multimodal challenges experienced by the student, the students rediverted the whole groups’ attention to the wrong connection of the wires. Although Lin and Lo (2017) reported that monologue is helpful in developing students’ thematic patterns, these strategies were not useful in the practical work reported here. Multimodal challenges in practical work reduced the effectiveness of some of the thematic development strategies such as monologue. In some cases, students can capitalize *afforded opportunities* to co-construct thematic patterns. In the excerpt in Table 5, although the teacher did not offer help in constructing thematic patterns, students picked up the opportunity immediately to explain the location and the use of chlorine (refer to thematic pattern 2 in Figure 3). But these occasions were very rare in the lesson.

The findings of this study add to the literature based by expanding the framework of Millar and Abrahams (2009) by highlighting the challenges and the corresponding strategies in practical work (refer to Figure 4). Practical work in typical science classrooms has long been argued that it cannot promote students’ development of scientific understanding. However, seldom do researchers look at this issue from the perspective of multimodal challenges. Though some research studies have reported that multimodality can help students make meaning of science concepts (Jaipal 2010; Kress et al. 2001), its semiotic potential should be carefully considered in the context of practical work. More importantly, some of the thematic development strategies might not be useful in facilitate students’ construction of thematic patterns. The expanded framework provided in Figure 3 and some challenges and corresponding strategies in Figure 4 can provide some recommendations for teacher educators who want to promote the effectiveness of practical work in their community. Teacher educators should first develop teachers’ awareness of these multimodal challenges. They can work with teachers to think of ways to promote students’ understanding of different modes of representations, or to mediate student-student discussion of the different modes of representations during practical work session.

From the purposeful class sample, only a group of eight students is included in this study. The small and male-dominated sample prevents generalisations. Speech from students sometimes cannot be captured as the camera cannot detect their voices. Although member checking is done on the transcripts, different academics may come up with different themes from the data. But we conducted the thematic analysis based on the framework from Millar and Abrahams (2009) and went back and forth both the data and framework for several times. This will help increase the reliability of the themes.

References

Author 1 (2018).

645 Author 1 (under revision)

646 Author 2 (under review)

647 Author 2 (on-going)

648 Abrahams, Ian, and Robin Millar. "Does practical work really work? A study of the
649 effectiveness of practical work as a teaching and learning method in school
650 science." *International journal of science education* 30, no. 14 (2008): 1945-1969.

651 Ainsworth, Shaaron. "DeFT: A conceptual framework for considering learning with multiple
652 representations." *Learning and instruction* 16, no. 3 (2006): 183-198.

653 Axelsson, Monica, and Britt Jakobson. "Negotiating science-building thematic patterns of the
654 scientific concept sound in a Swedish multilingual lower secondary
655 classroom." *Language and Education* (2020): 1-20.

656 Banchi, Heather, and Randy Bell. "The many levels of inquiry." *Science and children* 46, no.
657 2 (2008): 26.

658 Brown, Bryan A., and Eliza Spang. "Double talk: Synthesizing everyday and science
659 language in the classroom." *Science Education* 92, no. 4 (2008): 708-732.

660 Cheng, Maurice MW, and John K. Gilbert. "Students' Visualization of Diagrams Representing
661 the Human Circulatory System: The use of spatial isomorphism and representational
662 conventions." *International Journal of Science Education* 37, no. 1 (2015): 136-161.

663 Coll, C., and J. Onrubia. "Temporal dimension and interactive processes in teaching/learning
664 activities: a theoretical and methodological challenge." *Explorations in socio-cultural
665 studies* 3 (1994): 107-122.

666 Erduran, Sibel, and Zoubeida R. Dagher. "Reconceptualizing nature of science for science
667 education." In *Reconceptualizing the nature of science for science education*, pp. 1-
668 18. Springer, Dordrecht, 2014.

669 Erduran, Sibel, Yasmine El Masri, Alison Cullinane, and Y. P. D. Ng. "Assessment of
670 practical science in high stakes examinations: a qualitative analysis of high
671 performing English-speaking countries." *International Journal of Science
672 Education* 42, no. 9 (2020): 1544-1567.

673 Halliday, Michael Alexander Kirkwood. *Language as social semiotic: The social
674 interpretation of language and meaning*. Hodder Arnold, 1978.

675 Hodson, Derek. "Practical work in science: Time for a reappraisal." (1991): 175-184.

676 Hodson, Derek. "Re-thinking old ways: Towards a more critical approach to practical work in
677 school science." (1993): 85-142.

678 Jaipal, Kamini. "Meaning making through multiple modalities in a biology classroom: A
679 multimodal semiotics discourse analysis." *Science education* 94, no. 1 (2010): 48-72.

680 Jewitt, Carey, Gunther Kress, Jon Ogborn, and Charalampos Tsatsarelis. "Exploring learning
681 through visual, actional and linguistic communication: The multimodal environment
682 of a science classroom." *Educational Review* 53, no. 1 (2001): 5-18.

683 Kress, Gunther, Tsatsarelis Charalampos, Carey Jewitt, and Jon Ogborn. *Multimodal teaching
684 and learning: The rhetorics of the science classroom*. Bloomsbury Publishing, 2006.

685 Kress, Gunther, Jon Ogborn, and Isabel Martins. "A satellite view of language: some lessons
686 from science classrooms." *Language awareness* 7, no. 2-3 (1998): 69-89.

687 Feldon, David F., Briana Crotwell Timmerman, Kirk A. Stowe, and Richard Showman.
688 "Translating expertise into effective instruction: The impacts of cognitive task
689 analysis (CTA) on lab report quality and student retention in the biological
690 sciences." *Journal of research in science teaching* 47, no. 10 (2010): 1165-1185.

691 Lemke, Jay L. *Talking science: Language, learning, and values*. Ablex Publishing
692 Corporation, 355 Chestnut Street, Norwood, NJ 07648 (hardback: ISBN-0-89391-
693 565-3; paperback: ISBN-0-89391-566-1)., 1990.

694 Leonard, William H., and William A. Leonard. "A recipe for uncookbooking laboratory

- investigations." *Journal of College Science Teaching* (1991): 84-87.
- Lin, Angel MY, and Yuen Yi Lo. "Trans/languageing and the triadic dialogue in content and language integrated learning (CLIL) classrooms." *Language and Education* 31, no. 1 (2017): 26-45.
- Matthiessen, Christian MIM, and Jack Pun. "Expounding knowledge through explanations: Generic types and rhetorical-relational patterns." *Semiotica* 2019, no. 227 (2019): 31-76.
- Millar, Robin, and Ian Abrahams. "Practical work: making it more effective." *School Science Review* 91, no. 334 (2009): 59-64.
- Millar, Robin, Fred Lubben, Richard Got, and Sandra Duggan. "Investigating in the school science laboratory: conceptual and procedural knowledge and their influence on performance." *Research Papers in Education* 9, no. 2 (1994): 207-248.
- McNeill, David, Susan D. Duncan, Jonathan Cole, Shaun Gallagher, and Bennett Bertenthal. "Growth points from the very beginning." *The Emergence of Protolanguage: Holophrasis Vs Compositionality* 24 (2010): 117.
- National Research Council. *America's lab report: Investigations in high school science*. National Academies Press, 2006.
- Prain, Vaughan, and Bruce Waldrup. "An exploratory study of teachers' and students' use of multi-modal representations of concepts in primary science." *International Journal of Science Education* 28, no. 15 (2006): 1843-1866.
- Pun, Jack KH. "Salient language features in explanation texts that students encounter in secondary school chemistry textbooks." *Journal of English for Academic Purposes* 42 (2019): 100781.
- Roberts, R., and R. Gott. "Investigations: Collecting and using evidence." *Teaching secondary scientific enquiry* (2002): 18-49.
- Tang, Kok-Sing, Seng Chee Tan, and Jennifer Yeo. "Students' multimodal construction of the work-energy concept." *International Journal of Science Education* 33, no. 13 (2011): 1775-1804.
- Tang, Kok-Sing. "Instantiation of multimodal semiotic systems in science classroom discourse." *Language Sciences* 37 (2013): 22-35.
- Toplis, Rob, and Michael Allen. "'I do and I understand?' Practical work and laboratory use in United Kingdom schools." *Eurasia Journal of Mathematics, Science and Technology Education* 8, no. 1 (2012): 3-9.
- Rod Watson, J., Julian RL Swain, and Cam McRobbie. "Students' discussions in practical scientific inquiries." *International Journal of Science Education* 26, no. 1 (2004): 25-45.
- Sang, David, and Valerie Wood-Robinson, eds. *Teaching secondary scientific enquiry*. John Murray, 2002.
- Williams, Melanie. "Fifth graders' use of gesture and models when translanguaging during a content and language integrated science class in Hong Kong." *International Journal of Bilingual Education and Bilingualism* (2020): 1-20.